

Influence of the Interaction Length on the Diffraction Efficiency in an Air-Based Acousto-Optic Modulator

Regina Schuster^a, Clara Cecilia Uber^a, Marius Foith^a, Yannick Schrödel^{bcd}, Sören Soennecken^e, Jan Helge Dörsam^e, Mario Kupnik^e, Christoph M. Heyl^{bcd}, Anne Harth^a

^aAalen School of Applied Photonics, Aalen University

^bMeasurement and Sensor Technology Group, Technische Universität Darmstadt

^cDeutsches Elektronen-Synchrotron DESY

^dHelmholtz Institute Jena

^eGSI Helmholtzzentrum für Schwerionenforschung GmbH

mailto:regina.schuster@hs-aalen.de

This study investigates the influence of the effective acousto-optic interaction length on the diffraction efficiency in an air-based acousto-optic modulator (AOM). Therefore, a star-shaped multi-pass setup is applied to control the number of acousto-optic interaction passes in ambient air. A simulation model is developed and validated against the experimental diffraction pattern.

1 Motivation

Solid-state acousto-optic modulators (AOM) are commonly used for laser beam diffraction. However, their applicability is limited by the optical transparency range and laser-induced damage threshold of the employed solid materials. Under suitable conditions, air-coupled high-power ultrasonic fields (sound frequency: $f_{\text{sound}} = 490 \text{ kHz}$) enable contactless laser beam manipulation at a laser wavelength of $\lambda_{\text{laser}} = 1030 \text{ nm}$ [1].

The main challenge of air-based AOM is the weak refractive index modulation induced by the acoustic field ($\Delta n_{\text{sound}} \approx 10^{-6}$), resulting in low diffraction efficiency. Therefore, the sound-induced optical path difference ($\text{OPD}_{\text{sound}} = \Delta n_{\text{sound}} \cdot L_{\text{interact}}$) can be enhanced by propagating multiple times through the acoustic field, and thus increasing the effective acousto-optic interaction length L_{interact} .

Commercial ultrasonic transducers with an operating frequency of $f_{\text{sound}} = 40 \text{ kHz}$ represent attractive, practical options for such experiments, as an array of these transducers, in combination with an appropriate waveguide structure [2], can provide sufficiently high acoustic sound pressure levels ($\text{SPL} \approx 147 \text{ dB}$). In the following, the influence of the acousto-optic interaction length on the diffraction efficiency of an AOM operating in ambient air is investigated in simulation and experiment.

2 Simulation and Single-pass Experiment

Ultrasonic fields at 40 kHz with various optical wavelengths lead to an acousto-optic interaction in the Raman-Nath regime [3]. To predict the expected diffraction patterns, a simulation model is developed in which an ultrasound-induced phase grating is applied to the incident laser beam. Therefore, the acoustic input parameters of the simulation, such as $\text{OPD}_{\text{sound}}$, are determined interferometrically with a

Fizeau interferometer [4]. The resulting electric field is propagated into the far field using a Fraunhofer propagator in the Fourier domain [5].

For the acousto-optic measurements, a pulsed laser diode ($f_{\text{rep}} = 40 \text{ kHz}$, Duty Cycle: $DC = 25\%$) with an optical wavelength of $\lambda_{\text{laser}} = 638 \text{ nm}$ is used. A pulsed laser source is required due to the oscillating behavior of the standing acoustic wave. The beam diameter is expanded to $2w_{\text{laser}} = 17 \text{ mm}$ to cover approximately two acoustic wavelengths ($\lambda_{\text{sound}} = 8.6 \text{ mm}$), and the angle of incidence of the laser is $\theta_{\text{in}} = 0^\circ$.

Finally, this allows for the experimental validation of the simulated diffraction patterns (see Fig. 1).

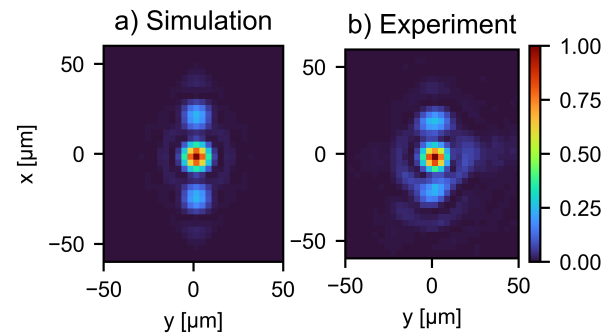


Fig. 1 Comparison between a) simulation and b) experiment - far field diffraction pattern after single pass ($\text{OPD}_{\text{sound}} = 56 \text{ nm}$) acousto-optic interaction.

After a single pass interaction in ambient air (see Fig. 1 b), the measured diffraction pattern already shows the $\pm 1^{\text{st}}$ diffraction order. This demonstrates Raman-Nath diffraction behavior.

3 Multi-Pass Setup and Results

An increase in the effective acousto-optic interaction length changes the diffraction efficiency per

order. This behavior is simulated, and the resulting diffraction efficiency follows the Bessel functions of the corresponding diffraction order (see Fig. 3, solid lines) [6].

To experimentally analyze the diffraction efficiency along the interaction length, a star-shaped mirror configuration is employed, enabling multiple acousto-optic interaction passes (see Fig. 2). Depending on the number of applied mirrors (0 to 20), the number of interaction passes can be adapted from a single-pass to 21 passes through the sound field.

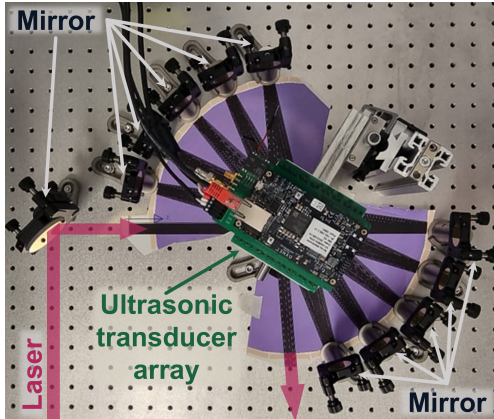


Fig. 2 Acousto-optic interaction area of the star-shaped multi-pass setup (10 mirrors in use; 11 passes through the sound field) and the indicated beam path.

Assuming a rotationally symmetric acoustic field, the main advantage of this multi-pass setup is that, for each pass, the laser beam propagates through the sound field at the same relative position. However, this position is not centered relative to the ultrasonic field.

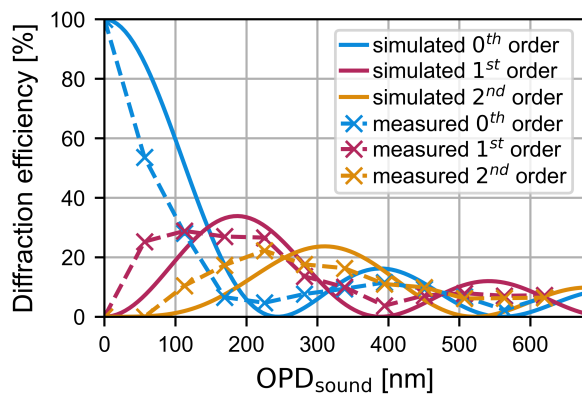


Fig. 3 Diffraction efficiency (0th order: blue, $\pm 1^{\text{st}}$ order: red, and $\pm 2^{\text{nd}}$ order: orange) along the acousto-optic interaction length; comparison of the theoretical Bessel function (—) and experimental measurement data (×).

Fig. 3 shows the quantitative measurement results of the diffraction efficiency and the theoretical Bessel function. For clarity, however, only 3 orders (0th, $\pm 1^{\text{st}}$, and $\pm 2^{\text{nd}}$) are presented in Fig. 3.

With an increasing number of passes, higher diffraction orders become clearly visible. After 10 passes ($\text{OPD}_{\text{sound}} = 560 \text{ nm}$), up to ± 8 diffraction orders can be detected.

4 Discussion

The experimentally detected first order demonstrates a strong appearance at its first maximum, with a diffraction efficiency of $\eta_1 = 25.5 \% \pm 3.6 \%$. The measurement data follow the dynamic behavior of the simulated data but exhibit deviations. These can be attributed to four primary causes: the relatively long pulse duration of the laser ($\tau = 6.25 \mu\text{s}$), the negative influences of the star-shaped setup, the assumption of a rotationally symmetric acoustic field, and the appearance of nonlinear acoustic effects. This nonlinear acoustic behavior becomes significant at high sound pressure levels, as provided by the transducer array. Nonlinear acoustics lead to waveform steepening, thus causing the diffraction efficiency to deviate from the ideal Bessel functions. This phenomenon was not considered in the simulation so far. However, in the future, interferometric measurements [4] of these nonlinear effects and their impact should be incorporated into the simulation model.

Please note that the number of interaction passes can only be measured as an integer, which may result in the actual extrema not being included in the measurement results ($\Delta\text{OPD} = 56 \text{ nm}$).

5 Conclusion

The influence of the acousto-optic interaction length on the diffraction efficiency distribution in an air-based acousto-optic modulator was investigated. The Fourier-based simulation and the star-shaped multi-pass experiments showed good agreement and confirmed the expected Raman–Nath diffraction behavior. This demonstrates the potential of a 40 kHz gas-based loss modulator, as the zeroth diffraction order can be tuned from 100 % down to approximately 5 %. Although quantitative deviations from the theoretical Bessel function were observed, the results provide a deeper understanding of acousto-optic interactions in air and contribute to the further development of air-based acousto-optic modulators.

References

- [1] Y. Schrödel et al., *Nature Photonics* **18**, 54–59 (2024).
- [2] M. Rutsch et al., *J. Acoust. Soc. Am.* **150**(5), 3228–3237 (2021).
- [3] W. R. Klein et al., *IEEE Transactions on sonics and ultrasonics* **14**(3), 123–134 (1967).
- [4] R. Schuster et al., *Optics & Laser Technology* **203**, 115538 (2026).
- [5] J. W. Goodman et al., vol. 1168 (Springer, 1996).
- [6] J. Gao et al., *Optica Applicata* **51**(3), 445–456 (2021).